

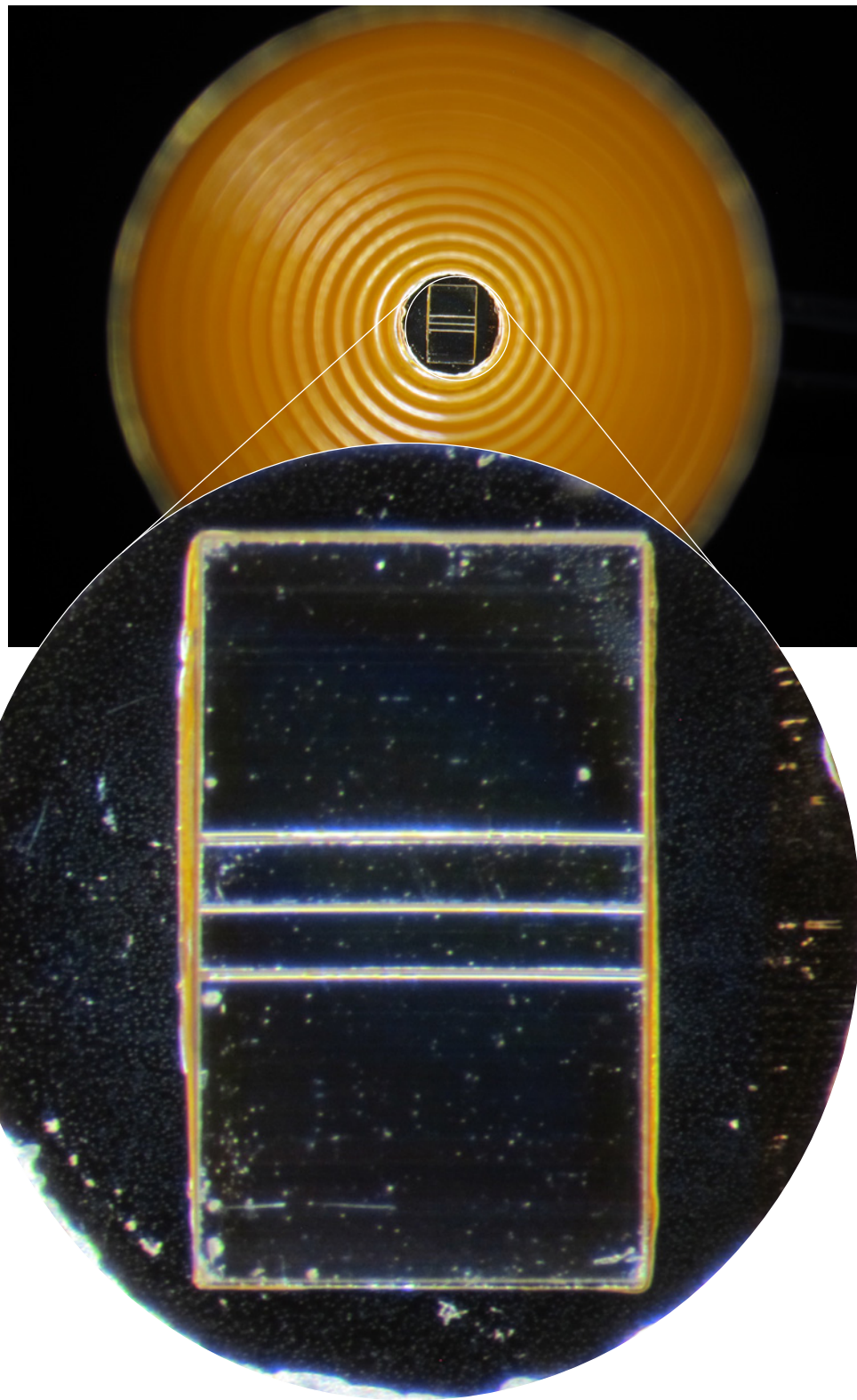
GENTLY COMPRESSING MATERIALS TO RECORD LEVELS

Experiments at the National Ignition Facility probe the equation of state of key materials made with unprecedented precision.

The setup for a ramp compression experiment at the National Ignition Facility (NIF) shows a cone-shaped device attached to the outside of the hohlraum wall. The device blocks stray laser light that can interfere with diagnostic measurements.

FROM the instantaneous detonation of a nuclear weapon or high explosive to the evolution of a planet's core over millions of years, a material's equation of state (EOS) is required to fully understand the relationship between its pressure, temperature, and density. Lawrence Livermore researchers must determine accurate EOS data of key elements to inform the computational models of material behavior that support National Nuclear Security Administration (NNSA) applications. These models drive simulations that demonstrate how materials respond to enormous pressures and high temperatures and help to assure that the nation's nuclear weapons remain safe, secure, and effective.

For the past decade, a team of scientists has been using Lawrence Livermore's National Ignition Facility (NIF), the world's largest and most energetic laser, to determine EOS data for solid materials at pressures never before achieved, up to 5 terapascals (TPa), or 50 million times Earth's ambient air pressure. Approximately 400 experiments are conducted at NIF annually, many of which support NNSA's Stockpile Stewardship Program, including inertial confinement fusion (ICF) experiments. For a few billionths of a second during an ICF experiment, NIF's 192 lasers duplicate the same temperatures, densities, and pressures found within the interiors of stars and planets and detonating nuclear explosives. About 15 experiments per year are aimed at researching materials' equations of state. In addition, about four shots a year are devoted to discovery science EOS experiments that help



A partial view of the physics package used in ramp compression experiments, as seen through the cone-shaped device attached to the hohlraum's outer wall, shows the stepped surface of the target material (inset). Using the cone to block out stray light, the VISAR (Velocity Interferometer System for Any Reflector) diagnostic (not shown) measures the speed at which each of the four steps move as the compression wave passes through them.

reveal the likely composition of stars and planets. (See the box on p. 9.)

For decades, the traditional method for determining a material's EOS was to send a sudden shock through a material and measure its response. This shock compression method relies on lasers, gas guns, and other tools to launch a virtually instantaneous shock wave through a sample, rapidly melting it. However, shock compression limits the combination of pressures, temperatures, and densities that may be reached to a narrow portion of the material's EOS. To reach a broader set of conditions, an alternative route—ramp compression—is proving immensely useful.

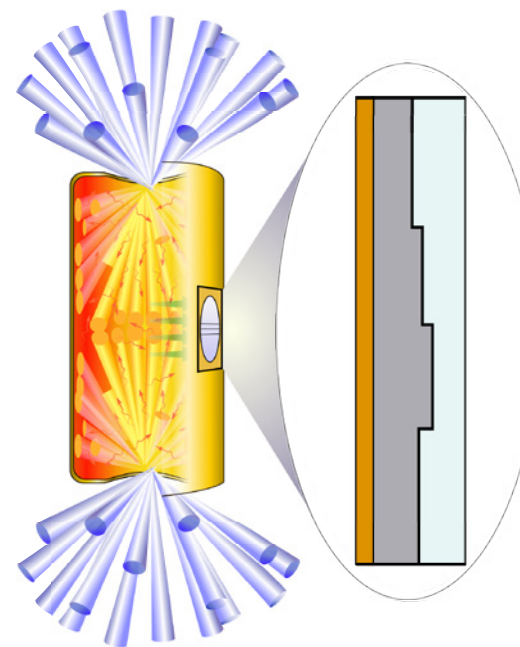
Creating a Gentler Compression

Ramp compression experiments on NIF apply a carefully tailored laser pulse shape that more “softly” compresses a material without forming a shock. Jon Eggert, group leader for Dynamic Materials Properties, explains, “NIF allows us to control the energy of the beams as a function of time so we can compress the sample more slowly. NIF is fantastic for ramp compression.” The technique is helping scientists better understand the physics of solids compressed to extreme densities under a wider range of pressures and much lower temperatures.

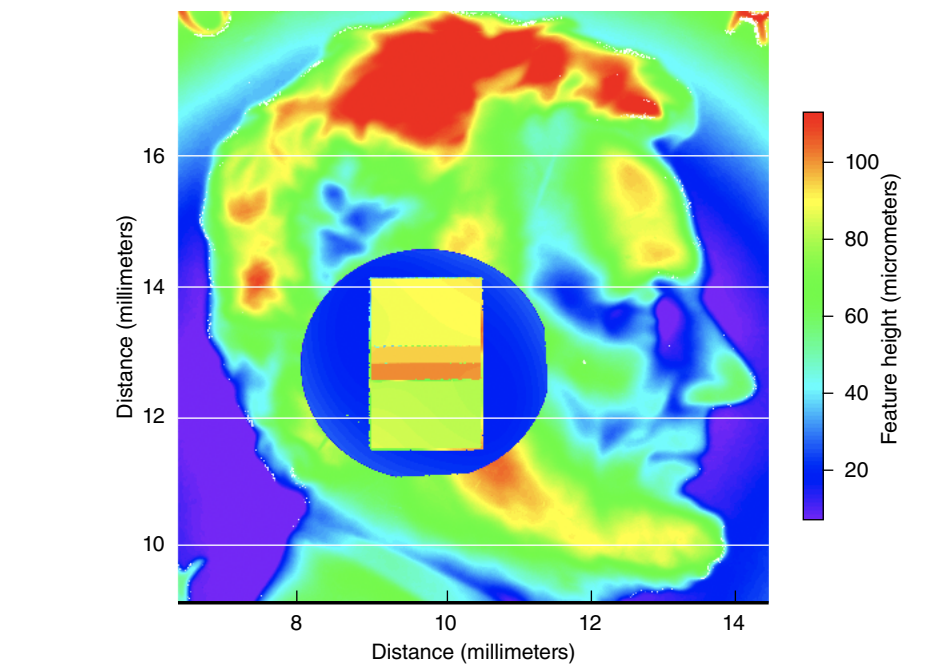
By controlling the laser's energy (up to 750 kilojoules) and power (up to 10 terawatts) over 31 nanoseconds (billionths of a second), scientists can customize the pulse shape precisely to match the material under investigation. “The quality of the pulse shape largely determines the quality of the EOS data,” says Tom Arsenlis, associate program director for Focused Materials Science. Simulations conducted by physicist Dave Braun are used to optimize the shape of the laser pulse. The simulations use a radiation hydrodynamics code that models the full geometry of the

laser and its target. Together, the laser's pulse-shape control, high energy and power, and state-of-the-art diagnostics make NIF the premier facility for ramp compression at pressures measured in TPa.

Ramp compression keeps the compressed target material relatively cool—less than 10,000 kelvin (about 9,700°C)—compared with 30 million kelvin in shock compression experiments. “We end up cool and extremely compressed,” says Livermore senior scientist Jim McNaney. During shock experiments, in contrast, most of the energy goes into heat, limiting the degree of compression to about



During ramp compression experiments, laser light enters the top and bottom of a hohlraum. The light is then converted to x rays, which heat and ablate the back side of a multilayered physics package placed over a tiny hole in the hohlraum's wall. (inset) The physics package consists of an underlying copper ablator (left), a four-step target material (middle), and a layer of lithium fluoride (right).



four times the starting density. “With ramp compression, we’re operating in regions where we have no existing data,” says McNaney.

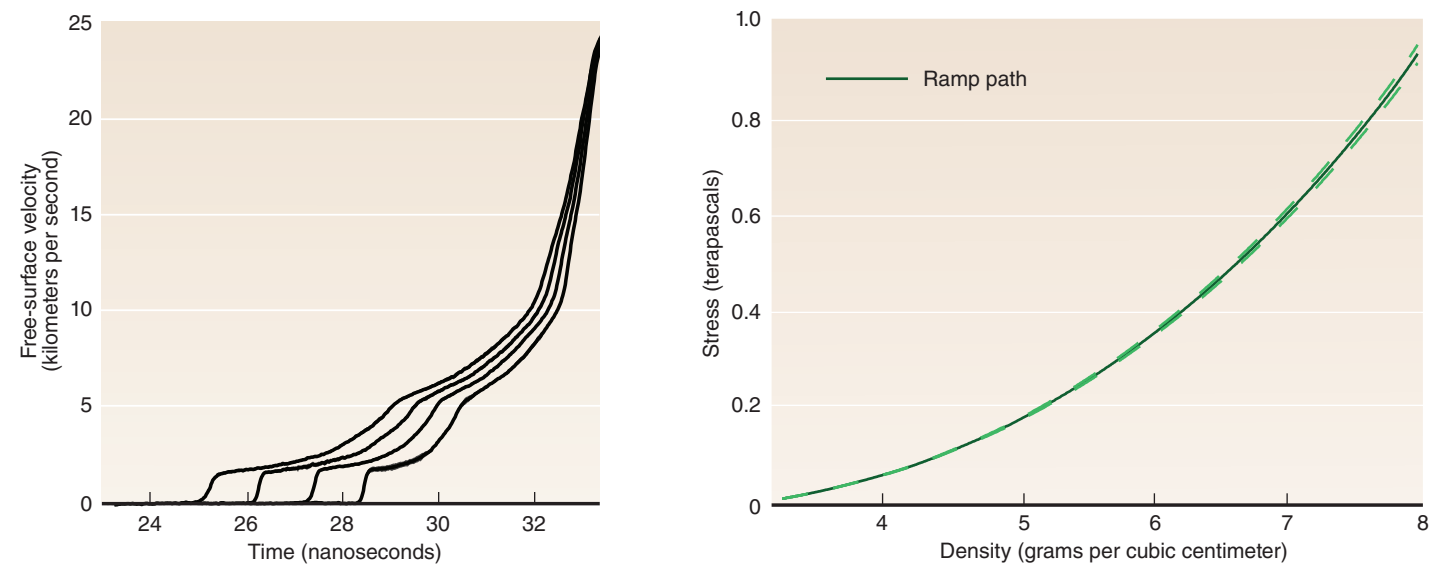
Ramp Compression Up Close

EOS ramp compression experiments at NIF typically use 168 of the facility's 192 beams. The light converges in the target chamber onto a tiny millimeter-sized, vertically aligned cylinder called a hohlraum. The hohlraum is filled with neopentane gas, which holds off collapse of the cylinder's gold-coated walls when they are hit by laser light. Thin windows at the top and bottom, where the laser light pours in, contain the gas until the initial, 2-nanosecond laser pulse blows out the windows. Subsequently, the pulse declines in energy, and then slowly increases (or ramps) over the next 29 nanoseconds as it crushes the target.

Upon illuminating the hohlraum walls, NIF laser light produces x rays that heat and ablate the back side of a multilayered physics package mounted over a 3-millimeter-diameter hole in the

Superimposed onto a penny is the minuscule stepped target attached to the underlying copper ablator (dark blue). The target is machined from one block into four different thicknesses ranging from approximately 50 to 100 micrometers. Colors represent the heights of the four steps as compared to those of the penny's features.

hohlraum's wall. The physics package consists of a circular underlying copper ablator (measuring 35 micrometers thick), a stepped target material—one block machined to four different thicknesses ranging from about 50 to 100 micrometers—and, frequently, a layer of transparent lithium fluoride. The copper ablator, irradiated by the x rays, drives a compression wave through the stepped target. The 300-micrometer-thick layer of lithium fluoride helps seal the material under investigation and prevents it from breaking up during a phase transition. The lithium fluoride window is transparent so that it will not interfere with the red laser used by the principal diagnostic called VISAR (Velocity



(left) Velocity profiles measured at the surface of the metal-coated lithium-fluoride sample show that thicker steps launch at a later time and display steeper rises from nonlinear compression. (right) A graph showing the final stress (pressure) versus density of the sample, with the curvature of the plot illustrating the nonlinear compression of the material. The dashed green lines represent the experimental uncertainty in the results.

Interferometer System for Any Reflector). “Lithium fluoride is nature’s clearest crystal,” says postdoctoral researcher Leo Kirsch.

VISAR Sees All

No instrument exists for directly measuring a material’s EOS. Instead, the team uses the VISAR diagnostic to record velocity versus time at various points on the surface of the stepped target during the experiment. VISAR measures the speed (typically to tens of kilometers per second) at which each of the four material steps move as the compression wave passes through them. Surrounded by a metal cone that keeps out stray laser light, VISAR captures the Doppler shift in wavelength (the phase change) of

reflected light over time caused by the compression wave. As the wave pushes through the material, the material’s density increases and so does its sound speed.

Analysis of VISAR data then reveals the sound speed, pressure, and density of the target material being compressed, from which the EOS is derived. “The experiments provide precise measurements of material properties to people who work on the codes, and the data helps to improve the predictions of the codes,” says Kirsch. In addition, post-shot simulations help prepare for follow-on experiments.

Methodical Platform Evolution

Eggert says that prior to the year 2000, ramp compression experiments were limited to about 0.01 TPa. Soon after, several additional tenths of a TPa were achieved. (As a point of reference, the center of the Earth is considered to be about 0.35 TPa). The EOS ramp compression platform for NIF was developed following experiments on Livermore’s Janus laser and then on the Omega laser at the University of Rochester’s Laboratory for Laser Energetics.

The first EOS ramp compression experiments at NIF focused on well-characterized materials such as copper, aluminum, and gold, to validate the experimental platform. Many experiments were conducted on gold because the material is a standard in the high-pressure community. Says physicist Amalia Fernandez-Panella, “We wanted to start with simple materials and develop analytical techniques with the goal of using much more complex elements comprising the actinides.” According to Livermore physicist Ray Smith, researchers have since demonstrated smooth EOS ramp loading pressures into the TPa regime on iron, platinum, lithium fluoride, diamond, tungsten, tantalum, iridium, lead, and tin. The campaign was initially headed by physicist Dayne Fratanduono and is now led by Smith.

Eggert notes that another method to determine EOS without imparting a violent shock uses small diamond anvil cells (DACs), a “static” technique Livermore researchers have helped to pioneer (*S&TR*, July/August 2019, pp. 20–23). DACs compress micrometer-sized samples between two brilliant-cut diamonds, generating pressures

of several tenths of a TPa. DAC experiments last much longer than NIF shots—from milliseconds to minutes to even days—generating temperatures much lower than NIF’s.

Another vehicle for EOS ramp compression experiments is Sandia National Laboratories’ Z Pulsed Power Facility, located in Albuquerque, New Mexico. At this facility, a series of large capacitors delivers up to 26 million amps to a centimeter-size target over a period of 100 to 200 nanoseconds. The facility produces pressures of 0.4 to 0.5 TPa and material temperatures similar to those in NIF EOS ramp compression experiments.

Three Different Campaigns

EOS experiments constitute one of three campaigns on high-energy-density materials involving ramp compression that provide important information for stockpile stewardship. McNaney leads the materials integrated experimental team, a group of 12 to 15 physicists who work on the three campaigns. He notes that while the two other campaigns—x-ray diffraction experiments called TARDIS (Target Diffraction In-Situ) and strength experiments—on their own generate vital data, they also “help us to interpret EOS data.”

In TARDIS experiments, ramp-compressed samples are probed with diffracted x rays from an x-ray source foil. The resulting diffraction lines provide insight into phase changes, or structural transitions, which can occur in materials under extreme pressure. In strength experiments, ripples imprinted in a material grow in response to the pressure wave as it pushes against the target. The ripples’ rate of growth is inversely related to the material’s strength. Physicist Suzanne Ali explains, “We measure different aspects of material response and then put everything together to obtain a more complete picture.”

Nearly Impossible Specifications

The tiny target sizes and demanding experimental requirements make data highly susceptible to manufacturing imperfections. As a result, multilayered EOS targets must meet precise specifications for dimensions, surface finish, and alignment.

As experimental diagnostics improve, an even greater demand for precision in target fabrication is sure to arise.

A team of about 15 machinists, engineers, assemblers, and mechanical designers is responsible for producing exquisitely machined targets that meet

Discovery Science Looks at Exoplanets

About 8 percent of overall shot time at the National Ignition Facility (NIF) is set aside for discovery science experiments that study the makeup of stars, planets, plasmas, and materials under extreme conditions. Physicist Ray Smith has been guiding many equation-of-state (EOS) experiments for the Discovery Science Program, which is open to researchers from outside the Laboratory.

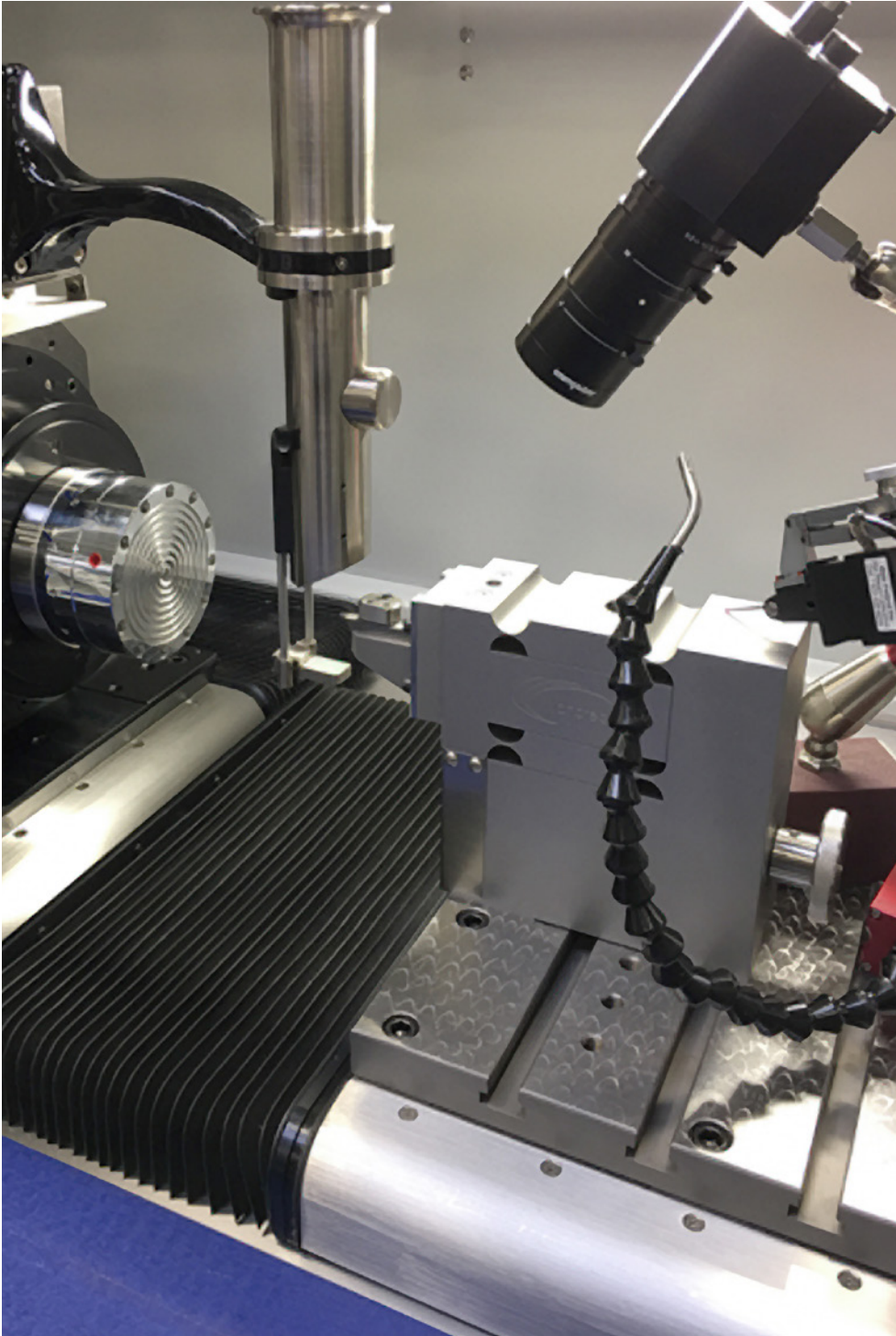
The reduced temperature generated by EOS ramp compression experiments at NIF makes these tests highly relevant to the study of high-pressure physics considered to underlie the structures of stars and, especially, planets both in our solar system and beyond. Thousands of extrasolar planets have been identified, some smaller than Earth and others more massive than Jupiter. NIF allows scientists to duplicate the extreme conditions considered to exist in their interiors.

Scientists are particularly interested in exoplanets known as “super Earths”—extrasolar bodies 3 to 20 times more massive than Earth, with pressures at their cores from 3 to 5 terapascals (TPa). EOS experiments at NIF provide clues to how these exoplanets might have formed billions of years ago, their interior makeup, and whether they could support an atmosphere or even sustain surface conditions suitable for some form of life.

Such planets are thought to contain an iron-alloy core, similar to Earth. A model of a planet’s interior cannot be directly based on EOS data gathered at high temperatures through shock compression experiments. Ramp compression experiments are more suitable because of the lower temperatures they produce. The standard technique for studying conditions relevant to the inside of planets used to be extrapolating data obtained with a diamond anvil cell (DAC). However, a DAC cannot produce the peak pressure of extrasolar super Earths (about 0.35 TPa), Saturn (4 TPa), Jupiter (7 TPa), and Neptune (0.8 TPa). Neither can DAC experiments produce the higher temperatures thought to exist in many planets’ cores. “The only way to recreate the interior conditions of large planets is through ramp compression on NIF,” says Smith.

Discovery science shots have used NIF to subject multiple thicknesses of diamond to ramp compression. (Carbon, from which diamond is formed, is important in planetary science.) Ice giant planets such as Neptune and Uranus may have diamond-rich layers in their interiors, as may exoplanets many times more massive than Earth. The team’s ramp compression experiments, conducted in 2011 and 2012, reached peak pressures of 5 TPa, 20 times higher than the pressure in previous DAC results.

NIF discovery science experiments on iron have aided the modeling of rocky planets including many super Earths. In 2018, a team from Lawrence Livermore, Sandia National Laboratories, Princeton University, the University of California at Berkeley, Johns Hopkins University, and the University of Rochester conducted EOS ramp compression experiments at NIF, generating pressures of 1.4 TPa. The team’s work was featured on the cover of the journal *Nature Astronomy* in 2018. The research is important because Earth’s magnetosphere, which helps to protect life from the Sun’s solar wind, magnetic storms, and harmful cosmic rays, may be generated by the circulating molten iron in Earth’s core.



During target fabrication, a camera projects onto a monitor a magnified image of the part being machined to capture its tiny dimensions.

increasingly exacting standards for thinness and uniformity. Any surface roughness (variation in thickness), for example, causes instabilities that distort the pressure wave and make data unreliable. As Livermore’s Target Fabrication Manager Abbas Nikroo notes, many of the precision machining and target assembly techniques used daily at NIF were developed both in-house and in conjunction with vendors. Nikroo points to a long Livermore history of precision machining and metrology (measurement science).

Most components are machined in a Lawrence Livermore facility equipped with high-precision diamond turning lathes capable of nanometer precision and mirror-like surface finishes. The machines are temperature controlled and isolated from vibration, including minute Earth tremors. To capture the targets’ tiny dimensions, a camera projects onto a monitor just above the machine a magnified picture of the part being machined.

Over a two-week period, the copper ablator, stepped target, and overlaying lithium fluoride window are slowly machined so that the thickness variation does not exceed 50 nanometers per millimeter and the stepped target has a surface finish comparable to a nearly perfect mirror. Parts are attached with a soluble adhesive to a 100-millimeter-diameter diamond-turned disk held by vacuum on a lathe spindle turning about 1,700 revolutions per minute. The adhesive accumulates in tiny grooves machined into the disk to ensure a smooth rear surface. Stepped targets are machined to the specified micrometer thicknesses and profile that are verified with double-sided white light interferometry to ensure uniformity and parallelism. Adding to the machining challenge is the requirement that the four miniscule steps be cut from a single block of material.

Approximately two weeks are required to assemble the physics package. Parts are secured by a uniform thickness of epoxy glue, which requires 16 hours to cure. All physics package components must be uniformly parallel as well as flat to ensure the pressure wave is planar during experiments.

Many Homegrown Machinists

Former Livermore target fabrication engineer Lila Ahrendes says, “An extremely skilled machinist is needed to make an EOS target to specifications.” Many machinists are from the optics industry, which often requires similar tolerances for military and space exploration components. About half of the machinists are graduates of Livermore’s own machinist apprenticeship program.

Ahrendes notes that, in 2018, NIF physicists asked the target fabrication team if it could halve the surface variation of the stepped targets. Achieving this extraordinary specification would reduce the uncertainty of the data obtained from each experiment by a factor of two, which in turn would reduce the number of EOS shots required for each material by a factor of four, saving three shots for each data point. Pascale Di Nicola, NIF deputy target production manager, credits senior engineering associate Carlos Castro for leading the successful effort to meet the stringent new specification. The 50-nanometer specification goal can be appreciated with this comparison: If the stepped target were scaled to the size of a football field and had the same flatness specification, the top of every blade of grass would have to be cut within the thickness of a No. 2 pencil lead, across the field’s 100 yards.

Castro also developed procedures for machining materials such as tantalum, which have not traditionally been considered for diamond turning because of their hardness or other qualities. One technique combines

artificial polycrystalline diamond, natural single-crystal diamond, and specialized cutting fluids to achieve the required specifications and mirror finish. The team also developed techniques for diamond-turning iridium, platinum, lead, and tin.

Plutonium Experiments Begin

For the past decade, the end goal of the NIF ramp compression EOS experiments has been the actinides, a group of 15 high-Z (atomic number) elements of the periodic table. One actinide of great interest is plutonium. NIF EOS experiments use isotopically pure plutonium-242 (^{242}Pu), the second longest-lived isotope (half-life of 373,300 years) of the element’s 20 isotopes. (NIF does not test weapons-grade plutonium.) In April 2019, the first ^{242}Pu ramp compression experiment was conducted on NIF, marking the start of an experimental campaign to better understand how the element compresses under extreme pressure.

The first ^{242}Pu shot exercised various aspects of forthcoming experiments on NIF, including special procedures for recovering ^{242}Pu debris. For example, VISAR was fitted with a device at one end to capture debris resulting from the extreme compression. This first experiment used an unstepped, flat surface of the isotope. However, the Laboratory is currently standing up a diamond-turning capability for making stepped targets from plutonium.

Platform Reaching Maturity

“We’ve made tremendous progress over the past few years,” says McNaney. “We’re right on target.” The EOS ramp compression platform—predictive codes, target fabrication, and pulse shaping—continues to advance. As the team prepares to continue the experimental series on ^{242}Pu , some researchers are working to find a way to measure temperature in EOS ramp



Target components are primarily machined in a Lawrence Livermore facility equipped with high-precision diamond turning lathes that are temperature controlled and isolated from vibration.

compression experiments. “Temperature is a very difficult thing to get a handle on, especially in ramp compression,” says Eggert. Physicists today must rely on models to derive temperature. However, Smith reports Livermore researchers are investigating two different methods to determine temperature and to incorporate the most promising technology.

Although materials do not give up their EOS secrets easily, NIF researchers have shown this gentle ramp compression method works extremely well for obtaining critical information. Thanks to an extraordinary facility and world-class target-machining capabilities, the next few years are sure to shed new light on materials under extreme pressure.

—Arnie Heller

Key Words: diamond anvil cell (DAC), discovery science, equation of state (EOS), exoplanet, National Ignition Facility (NIF), plutonium-242 (^{242}Pu) isotope, ramp compression, Stockpile Stewardship Program, super Earth, Z Pulsed Power Facility.

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